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# ABSTRACT

The recent availability of inexpensive, electrically addressable liquid crystal displays has generated interest in the use of such devices for optical processing applications. Characterizations pertinent to this use include: maximum obtainable modulation depth, modulation transfer function (MTF), linearity of response, refresh cycle time and optical flatness. Examples of device performance as a coherent processor and as an incoherent processor will be given.

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Edward Roy Raudenbush, 2LT, USAF

Feasibility Investigation into the Use of a Liquid Crystal
Television as a Spatial Light Modulator

The recent availability of inexpensive, electronically
addressable liquid crystal displays has generated interest in
the use of such devices for optical processing applications.
Characterizations pertinent to this use include: maximum
obtainable modulation depth, modulation transfer function
(MTF), linearity of response, refresh cycle time, and optical
flatness. Examples of device perfromance as a coherent
processor and as an incoherent processor will be given.

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Coordinator of Degree Program

COMMITTEE ON FINAL EXAMINATION     Louis M. Trefonas
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FEASIBILITY INVESTIGATION INTO
THE USE OF A LIQUID CRYSTAL TELEVISION
AS A SPATIAL LIGHT MODULATOR


BY

EDWARD ROY RAUDENBUSH
B.S.E., University of Central Florida, 1984


THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Engineering
in the Graduate Studies Program of the College of Engineering
University of Central Florida
Orlando, Florida


Spring Term
1986

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# CHAPTER I

## SPATIAL LIGHT MODULATORS

### Introduction

A spatial light modulator (SLM), sometimes called a light valve, is an electro-optic device which modulates light by means of some control mechanism. SLMs are used extensively in modern electro-optic systems. For example, a spatial light modulator may be used in the Fourier plane to affect filter operations or to enhance an image. SLMs are also used as input transducers for optical computing systems. Signal processing applications include real-time optical correlation, processing of radar signals and other real-time or pseudo real-time operations (Casasent 1978).

Spatial light modulators have been fabricated based on a number of physical mechanisms including electro-optic, acousto-optic, magneto-optic, liquid crystal re-orientation, deformable membrane, thermoplastic and a host of others (Casasent 1977). Many of these devices were originally conceived for display or mass storage applications.

### Classification of Spatial Light Modulators

Spatial light modulators may be classified according to the method by which they are addressed (Casasent 1980). They may be addressed optically or electronically. There are three primary

methods of electronically addressing a spatial light modulator: by a charge coupled device (CCD) array interfaced to the modulating material, by an electroded matrix deposited on the surface of the device or by scanning a modulated electron beam across the active surface area. Electronically addressed SLMs include the ERIM Thermoplastic Light Valve (TOPR) and the Semetex Sight Mod (formerly the Litton Magneto-optic Spatial Light Modulator). In the case of the TOPR, the modulating medium, thermoplastic, is spatially deformed by the charge deposited by a scanning electron beam. The TOPR has a resolution of 32 LP/mm at 50% modulation and a limiting resolution of 50 LP/mm at 5% modulation (Casasent 1980). This device has a dynamic range of 400:1, but requires a high voltage (7000 v) for operation. The Sight Mod has a limiting resolution of 6.56 LP/mm (128 x 128 array version). The Sight Mod may be driven by a standard IBM driver interface card. The Sight Mod and interface card cost approximately $18,700 as of February 1986. An optically addressable spatial light modulator may be addressed in four principle ways: by point to point scanning with a modulated laser beam, by recording a holographic interference pattern on the active area of the device, by recording the input data one line at a time or by a spatially modulated light distribution imaged onto the device. Examples of optically addressable spatial light modulators are Hughes Hybrid Liquid Crystal Light Valve and the Itek Pockels Readout Optical Modulator (PROM). The Hughes liquid crystal SLM has a resolution of 30 LP/mm at 50% modulation and has a limiting resolution of 70

LP/mm at 5% modulation (Casasent et al. 1978). It has a dynamic
range of 100:1, and requires only 6 volts at 10 KHz for operation.
The Hughes liquid crystal light valve costs approximately $25,000
as of February 1986.

### A Low Cost Spatial Light Modulator

This thesis addresses the characterization and application of
a low cost liquid crystal display device, the Radio Shack Model 16-151
Pocketvision television, as a spatial light modulator. This device
is commercially available as of this writing for under $200. The
LCTV is addressed electronically, via an electroded matrix deposited
on the surface of the SLM. The matrix is accessed by applying a
composite video signal to the liquid crystal television.

### Theory of Operation of the LC Display

The liquid crystal display panel used on the Radio Shack
Pocketvision utilizes a nematic liquid crystal material. Liquid
crystals are rod-like molecules which are neither crystalline solids
nor isotropic liquid (Blinov 1983). These molecules are ordered in
only one or two dimensions, while molecules in a solid crystalline
lattice are ordered in all three dimensions. Nematic type liquid
crystal molecules are ordered in only one dimension, while remaining
randomly oriented in the other two dimensions. Liquid crystal
displays rely on the alteration of the nematic phase structure by
the application of an electric field, called the twisted nematic
effect (Apt 1985). These structural changes affect the transmission

of polarized light passing through the liquid crystal material.
When the device is assembled, the liquid crystal molecules have a
spiral structure twisted about their centers. A polarizer is placed
on top of the display, controlling the polarization of the incoming
light. When light enters the liquid crystal material, the direction
of polarization is rotated as the light traverses the spiral
configuration of the liquid crystal medium. A second polarizer,
acting as an analyzer, is placed at the bottom of the display,
oriented to pass the light whose polarization has been altered by
the spiral structure. Hence, the display appears "light" to an
observer. When a voltage greater than the threshold voltage is
applied to an individual picture element (pixel), liquid crystal
molecules in the affected area change their physical orientation.
This affects the polarization of the light passing through this area,
making this area appear "dark" to an observer. Note that this is
not a binary operation. Recall, Malus' law relates the change in
irradiance of light transmitted through a polarizer and an analyzer
as a function of the angle between the transmission axis of the
polarizer and the transmission axis of the analyzer (Mayer-Arendt
1972). This is shown by:

$$E_2 = E_1 \cos^2 \theta$$

where:

$E_1$ = the irradiance of the incident beam

$E_2$ = the irradiance of the transmitted beam

$\theta$ = the angular difference between the plane of polarization
and the analyzer plane

## Summary

Spatial light modulators are important devices in the field of optical processing. However, their use is severely limited due to their high cost. The Radio Shack Pocketvision LCTV provides an inexpensive alternative to the high cost, high performance models currently available ($18,700 for the Sight Mod, $25,000 for the Hughes LC light valve). In the following chapters, the liquid crystal TV will be characterized for use as a spatial light modulator. Application of the LCTV to coherent and incoherent processing will also be demonstrated. Finally, possible hardware modifications to the LCTV are proposed, along with additional areas of research and application.

## CHAPTER II

## CHARACTERIZATION OF THE LIQUID CRYSTAL
## TV AS A SPATIAL LIGHT MODULATOR

### Introduction

The Radio Shack liquid crystal TV was evaluated for use as a spatial light modulator. The LCTV has an active screen area of 4.75 cm horizontal by 4.05 cm vertical, with 140 pixels (picture elements) by 120 pixels. The pixel size is approximately 0.33 mm by 0.33 mm. The spacing between pixels is approximately 0.01 mm, as shown in Figure 1. This equates to a resolution of approximately 1.47 LP/mm (LP/mm = line pairs per mm). It operates on 6 VDC. The LCTV accepts standard composite video input, such as the output of a microcomputer, video cassette recorder or video camera. As a result of the low resolution of the device, the liquid crystal TV is incapable of displaying a full (700 pixel x 525 pixel) TV image. Instead, it displays a low resolution version of the input signal on its display screen, as opposed to cutting off scan lines.

For this work, a microcomputer was chosen to program the liquid crystal TV because of the computer's inherent flexibility. The host computer system chosen for this research was an Atari 1200XL computer with one disk drive. The Atari computer was used to generate the filter masks and test patterns which were displayed on the LCTV. The masks and test patterns were programmed using graphics mode 8 in
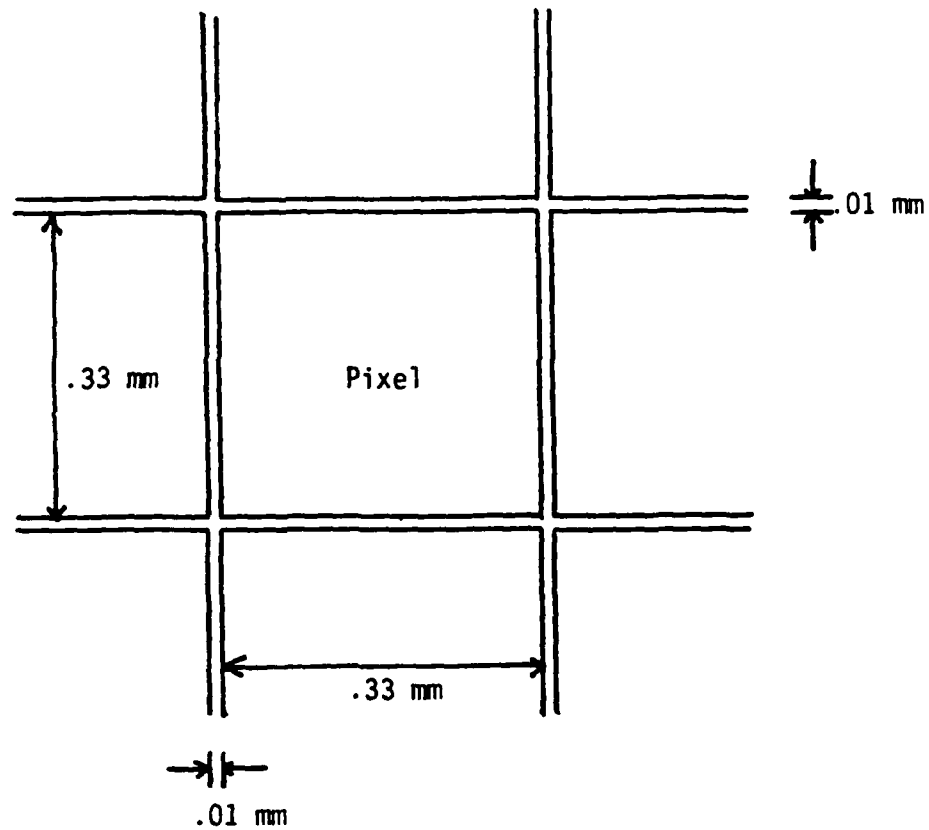
Figure 1. Liquid Crystal Pixel Structure.

Atari Basic. For additional information on the host computer's graphics display mechanism, the reader is referred to Appendix A.

The liquid crystal TV functions as a spatial light modulator by transmitting light through the liquid crystal display screen. To do this, the display screen must be separated from the main circuit board, as shown in Figure 2. Also, recall the LCTV display screen employs two polarizers, so the polarization of the incident light is critical to achieve maximum light transmission.
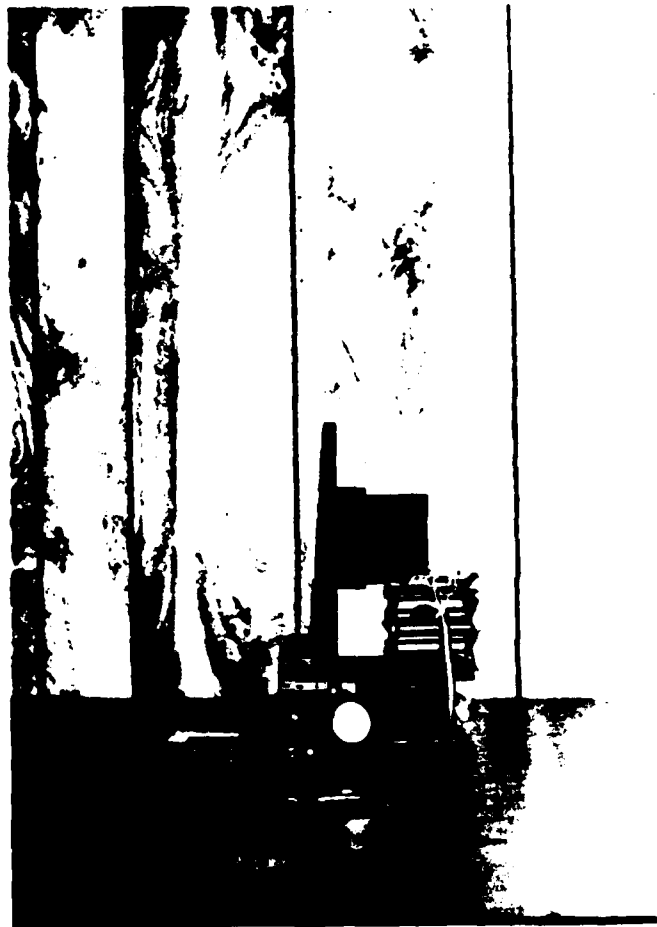
Figure 2. Picture of LCTV with Display Panel Separated.

A spatial light modulator is characterized by a number of important parameters including maximum obtainable modulation depth, modulation transfer function, linearity of response, optical flatness of the display screen and refresh cycle time (Casasent 1979). Our measurements of these parameters for our device were made using a helium-neon laser (632.8 nm).

## Maximum Obtainable Modulation Depth

Modulation depth, or contrast, is defined as (Hecht and Zajac 1979):

$$M = \frac{E_{max} - E_{min}}{E_{max} + E_{min}}$$

where:

$E_{max}$ = the maximum irradiance measured behind the SLM

$E_{min}$ = the minimum irradiance measured behind the SLM

A computer program (MOD.BAS, Appendix B) was written to allow measurement of maximum and minimum transmission of light through the liquid crystal display. This was done by creating a "white" graphics screen, equating to a maximum transmission condition. Similarly, minimum transmission was obtained using a "black" graphics screen. The modulation depth of the LCTV was varied by adjusting the "brightness" control. To allow for reproducibility in the measurements, the "brightness" control setting was equated to a reference voltage, $V_{ref}$. This reference voltage was measured on

PCB 1 (Radio Shack Service Manual, Model 16-151 Pocketvision). The test point was located adjacent to the middle of the ribbon cable connector. $V_{ref}$ was measured with a white graphics screen displayed on the LCTV. The maximum and minimum transmitted irradiances were measured as the "brightness" control was varied from maximum brightness ($V_{ref}$ = 3.36 v) to minimum brightness ($V_{ref}$ = 1.61 v) settings. The experimental set-up is shown in Figure 3. The percent transmission for each "brightness" control setting is plotted on Graph 1. The modulation depth for each "brightness" control setting is shown on Graph 2. The maximum obtainable modulation depth was 0.667 at $V_{ref}$ = 1.76 v, with 2.5% transmission. Greater transmission may be achieved at a reduced modulation depth.
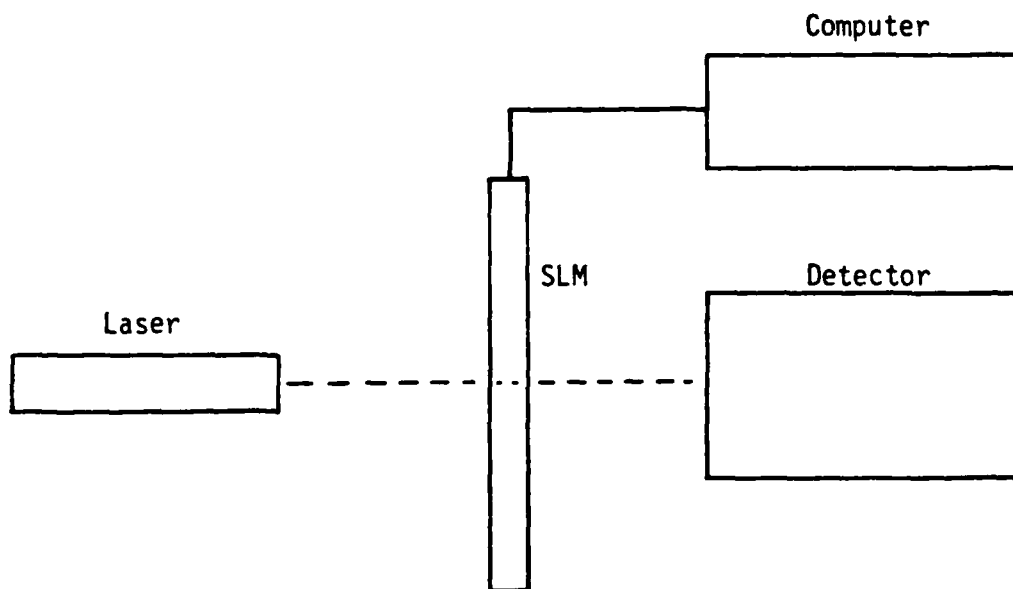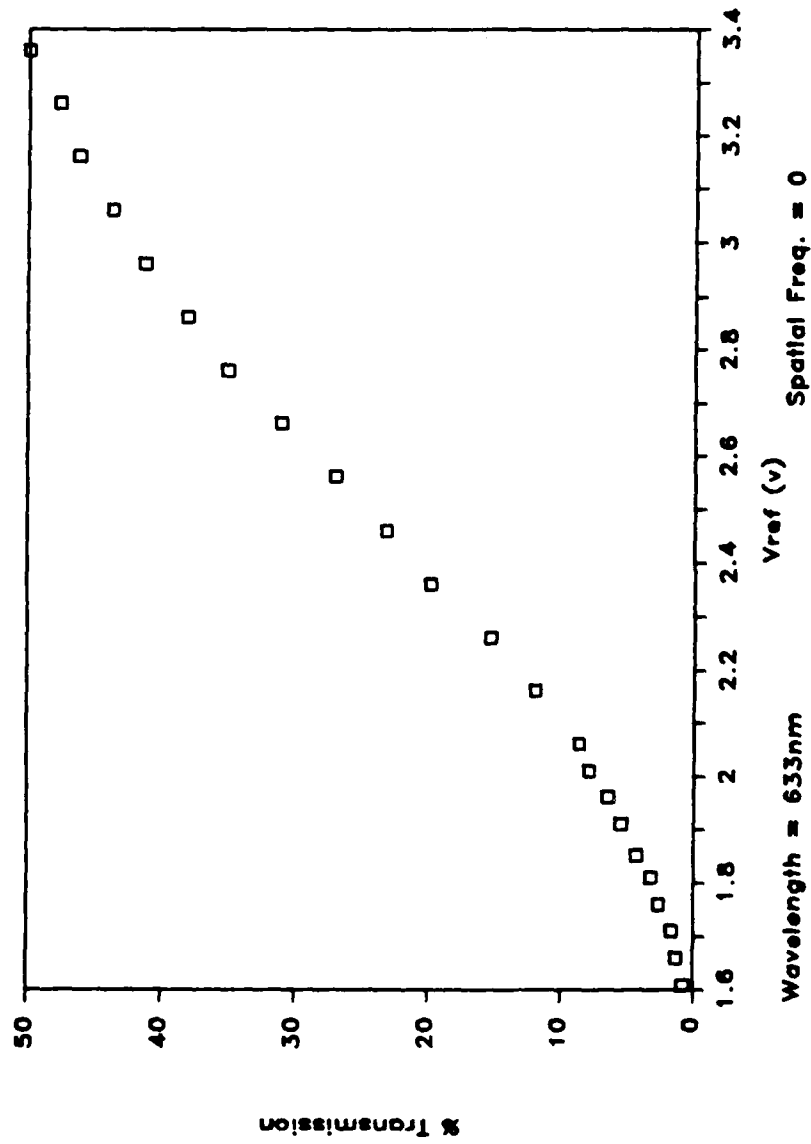
Figure 3. Experimental Set-up to Measure Modulation Depth.

Graph 1. Percent Transmission Versus $V_{ref}$.

Wavelength = 633nm    Spatial Freq. = 0

Vref (v)

12
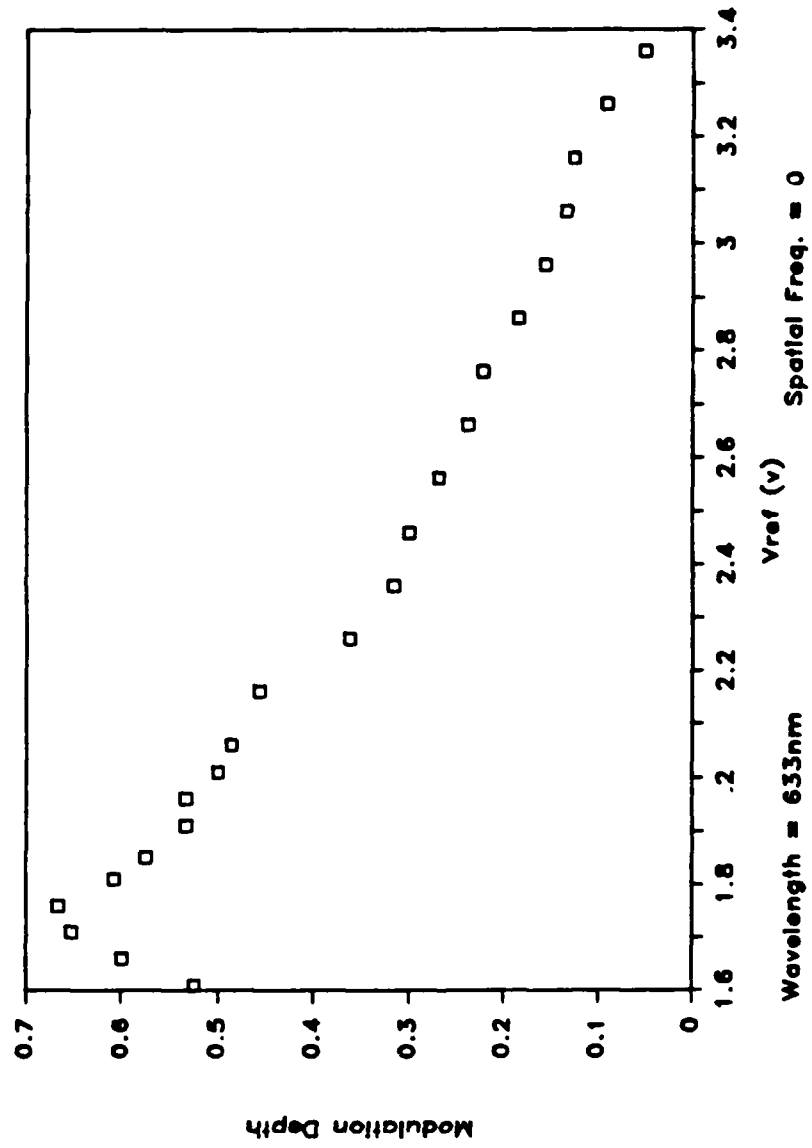


Graph 2.  Modulation Depth Versus $V_{ref}$.

## Modulation Transfer Function

The modulation transfer function (MTF) of a spatial light modulator specifies the normalized contrast of the device as a function of spatial frequency. This parameter is widely used to specify the performance of optical components and systems. If the individual MTFs of components in a system are known, the system MTF is simply the product of the individual MTFs (Hecht and Zajac 1979). Many techniques exist for the measurement of the MTF of an optical component. In this work, a series of alternating black and white bars were displayed on the LCTV. The width of the bars determined the spatial frequency under consideration. The "brightness" control was set to the point of maximum modulation depth ($V_{ref}$ = 1.76 v). By performing an inverse video operation (black to white, white to black), $E_{max}$ and $E_{min}$ transmitted were obtained. Recall the pixel size was approximately 0.33 mm by 0.33 mm. Hence, to measure the modulation transfer function to the limit of the SLM's resolution, the incident beam must have a diameter of less than 0.33 mm. The light source used, a Hughes Model 3225H-PC helium-neon laser, has a beam diameter at the $1/e^2$ point of 0.83 mm, with a divergence angle of 1 mrad (Hughes Laser Data Sheet). A lens must be used to reduce the diameter of the beam to an acceptable size. The following calculation is aimed at determining the focal length of this lens and the required geometry, as shown in Figure 4. Since the irradiance of this beam is a Gaussian function, we refer to Yariv's
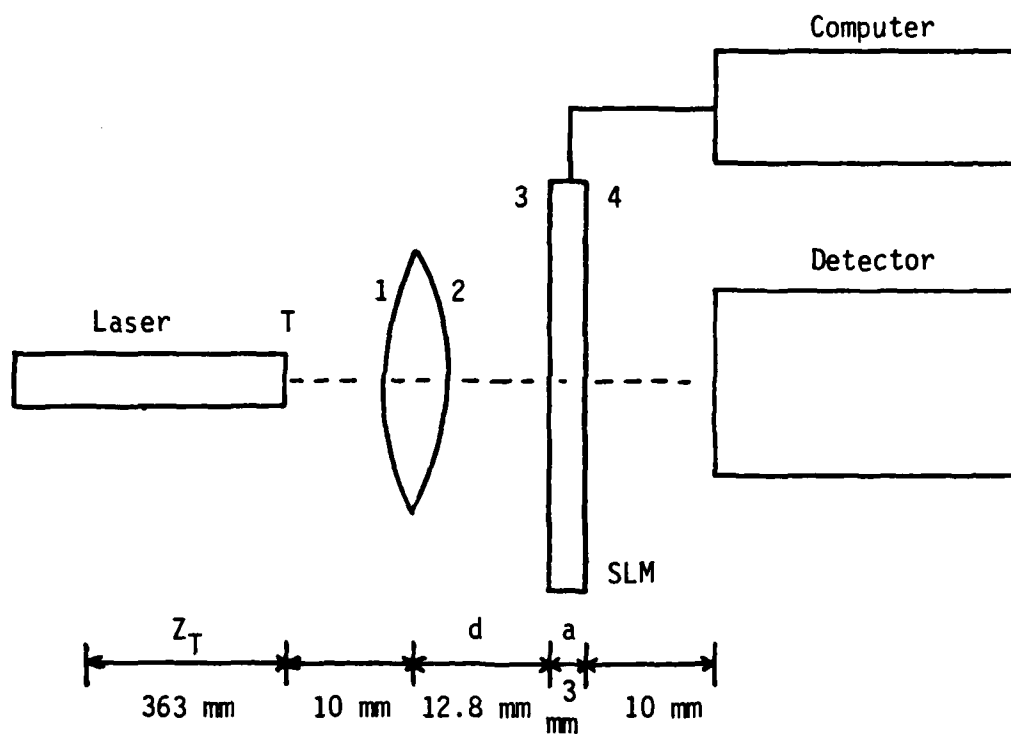
Figure 4.   Experimental Set-up to Measure MTF.

Optical Electronics, for a description of Gaussian beam propagation through a homogeneous medium (Yariv 1985).

Since the beam waist $(\omega_0)$ is not included on the specification sheet, we start by finding it.

$$\theta_{div} = \tan^{-1} \left(\frac{\lambda}{\pi \omega_0 n}\right), \quad \text{for } \theta_{div} < \pi$$

$$n = 1.0$$

$$\lambda = 632.8 \text{ nm}$$

$$\tan \theta_{div} = \frac{\lambda}{\pi \omega_0}$$

$$\omega_0 = \frac{\lambda}{\pi \tan \theta_{div}}$$

$$\omega_0 = 2.01 \times 10^{-4} \text{ m}$$

Following Yariv's development, the constant, $Z_0$, is now defined.

$$Z_0 = \frac{\pi \omega_0 n}{\lambda}$$

$$Z_0 = 0.201 \text{ m}$$

Figure 4 shows the experimental set-up used to determine the MTF for the LCTV. The detector used for these measurements was a UDT Model 40X Opto-meter. It is now necessary to find the location of the beam

waist, $\omega_0$, in reference to the laser head, point T. This distance, $Z_T$, may be determined since we know the diameter of the beam at the laser head ($\omega_T = 0.415$ mm).

$$\omega_T^2 = \omega_0^2 \left(1 + \frac{Z_T^2}{Z_0^2}\right)$$

$$Z_T = Z_0 \left(\frac{\omega_T^2}{\omega_0^2} - 1\right)^{\frac{1}{2}}$$

$$Z_T = 0.363 \text{ m}$$

Hence, the beam waist is located approximately 363 mm behind the laser head (point T). Referring to Figure 4, the semi-diameter of the beam at the first surface of the lens (point 1) is now determined.

$$\omega_1 = \left[\omega_0^2 \left(1 + \frac{Z^2}{Z_0^2}\right)\right] \qquad \text{where } Z = Z_T + .01 \text{ m}$$

$$\omega_1 = 4.24 \times 10^{-4} \text{ m}$$

The radius of curvature ($R_1$) at point 1 is now defined, as well as the complex radius of curvature ($q_1$) needed in subsequent derivation. $R_1 = |q_1|$.

$$R_1 = Z \left(1 + \frac{Z_0^2}{Z^2}\right)$$

$$R_1 = 0.482 \text{ m}$$

The ABCD Law is now employed to propagate through the lens, to point 2.

$$\begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$$

$$\frac{1}{q_i} = \frac{1}{R_1} - \frac{i \lambda}{n \pi \omega_1^2}$$

$$q_2 = \frac{A_2 q_1 + B_2}{C_2 q_1 + D_2} = \frac{q_1}{1 - q_1/f}$$

$$\frac{1}{q_2} = \frac{1}{R_2} - \frac{i \lambda}{n \pi \omega_1^2} = \frac{1}{q_1} - \frac{1}{f}$$

$$\frac{1}{R_2} - \frac{i \lambda}{n \pi \omega_2^2} = \frac{1}{R_1} - \frac{i \lambda}{n \pi \omega_1^2} - \frac{1}{f}$$

Equating imaginary parts, $\omega_1 = \omega_2$. Equating real parts:

$$\frac{1}{R_2} = \frac{1}{R_1} - \frac{1}{f} = \frac{f - R_1}{R_1 f}$$

The ABCD Law is again employed to propagate through air to the SLM, point 3.

$$\begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

$$q_3 = \frac{A_3 \, q_2 + B_3}{C_3 \, q_2 + D_3} = q_2 + d$$

$$\frac{1}{q_3} = \frac{\pi \, \omega_1^2 \, (f - R_1) - i \, \lambda \, f \, R_1}{\pi \, \omega_1^2 \, [d(f - R_1) + f \, R_1] - i \, \lambda \, f \, R_1 \, d}$$

Propagating from point 3 to point 4 (through the SLM):

$$\begin{bmatrix} A_4 & B_4 \\ C_4 & D_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & n_2/n_1 \end{bmatrix} \begin{bmatrix} 1 & a \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & n_1/n_2 \end{bmatrix}$$

$$\begin{bmatrix} A_4 & B_4 \\ C_4 & D_4 \end{bmatrix} = \begin{bmatrix} 1 & a \, n_1/n_2 \\ 0 & 1 \end{bmatrix} \qquad \text{where } n_1 = 1.0$$

$n_2$ = index of refraction for SLM

$$q_4 = \frac{A_4 \, q_3 + B_4}{C_4 \, q_3 + D_4} = q_3 + \frac{a}{n_2}$$

$$\frac{1}{q_4} = \frac{1}{q_3 + a/n_2}$$

$$\frac{1}{q_4} = \frac{\pi^2 \omega_1^4 (f-R_1)\{d(f-R_1)+fR_1+\frac{a}{n_2}(f-R_1)\}+i\pi\omega_1^2(f-R_1)\lambda fR_1[d+\frac{a}{n_2}]}{\pi^2\omega_1^4[d(f-R_1)+\frac{a}{n_2}(f-R_1)+fR_1]^2+\lambda^2 f^2 R_1^2[d+\frac{a}{n_2}]^2} -$$

$$\frac{i\pi\omega_1^2 \lambda fR_1\{d(r-R_1)+fR_1+\frac{a}{n_2}(f-R_1)\}+\lambda^2 f^2 R_1^2 \; d+\frac{a}{n_2}}{{}^2\omega_1^4[d(f-R_1)+\frac{a}{n_2}(f-R_1)+fR_1]^2+\lambda^2 f^2 R_1^2[d+\frac{a}{n_2}]^2}$$

Recall, we are determining the combination of lens and geometry to reduce the beam size to less than 0.33 mm as it passes through the SLM. At this point, only the imaginary part of $1/q_4$ is needed.

$$I_m(\frac{1}{q_4}) = \frac{-i\pi\omega_1^2\lambda f^2 R_1^2}{\pi^2\omega_1^4[d(f-R_1) + \frac{a}{n_2}(f-R_1) + fR_1]^2 + \lambda^2 f^2 R_1^2[d + \frac{a}{n_2}]^2} = \frac{-i\lambda}{\pi\omega_4^2}$$

$$\omega_4^2 = \frac{\pi^2\omega_1^4[d(f-R_1) + \frac{a}{n_2}(-R_1) + fR_1]^2 + \lambda^2 f^2 R_1^2[d + \frac{a}{n_2}]^2}{\pi^2\omega_1^2 f^2 R_1^2}$$

The semi-diameter of the beam, $\omega_4$, at point 4 (exiting the SLM) may now be computed. Hence, if the thickness of the LC display (a) is approximately 3 mm, the required lens has a focal length of about 15 mm (use a 10x microscope objective). The separation between the lens and the SLM (d) must be about 12.8 mm. Given the following lens and geometry, the beam diameter ($2\omega_4$) exiting the SLM was found to be approximately 0.03 mm. The beam diameter is now smaller than the pixel dimension (0.03 mm < 0.33 mm). This result is valid for an assumed index of refraction for the SLM of n = 1.5. Note, however, a valid result (beam diameter < 0.33 mm) is obtained if $1.4 < n_{SLM} < 1.6$.

The measurements were made and the formula for modulation depth was employed to determine the contrast at a specific spatial frequency. A computer program (MTF.BAS, Appendix B) was used to

measure the MTF from zero spatial frequency to approximately 1.47 LP/mm. The modulation transfer function is shown on Graph 3. The MTF curve is fairly flat from zero spatial frequency out to the limiting resolution of the device (measurements made at $V_{ref}$ = 1.76 v).

## Linearity of Response

The liquid crystal TV displays more than just binary information. The host computer can display 8 video intensity levels (Appendix A). Using the experimental set-up shown in Figure 3, the irradiance of the transmitted light was measured for each of these levels from black to white. The reference voltage was set to $V_{ref}$ = 1.91 v for these measurements. The program, VLEVEL.BAS (Appendix B), was used to select the appropriate video level. A plot of the normalized transmission versus the gray level is shown in Graph 4. Black represents level 0, and white represents level 7. We note that the transmitted light increased almost linearly with a linear change in the gray level from black to white.

## Optical Flatness

The optical flatness of the SLM surface determines how much phase distortion the SLM introduces into an optical processing system. Obviously, the flatter the optical surface, the less phase distortion is introduced (Malacara 1978).

Typically, an interferometer is used to measure this surface flatness. For this work, a Zygo interferometer was used. We found
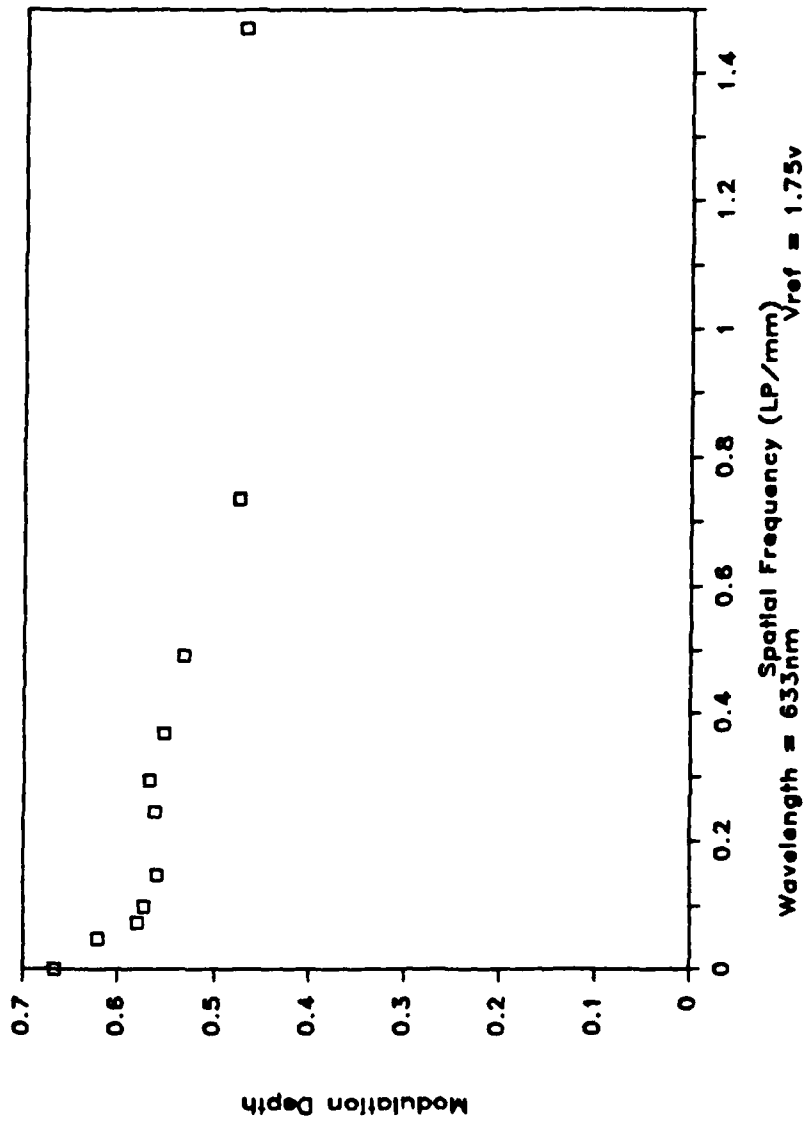
Graph 3. Modulation Transfer Function.
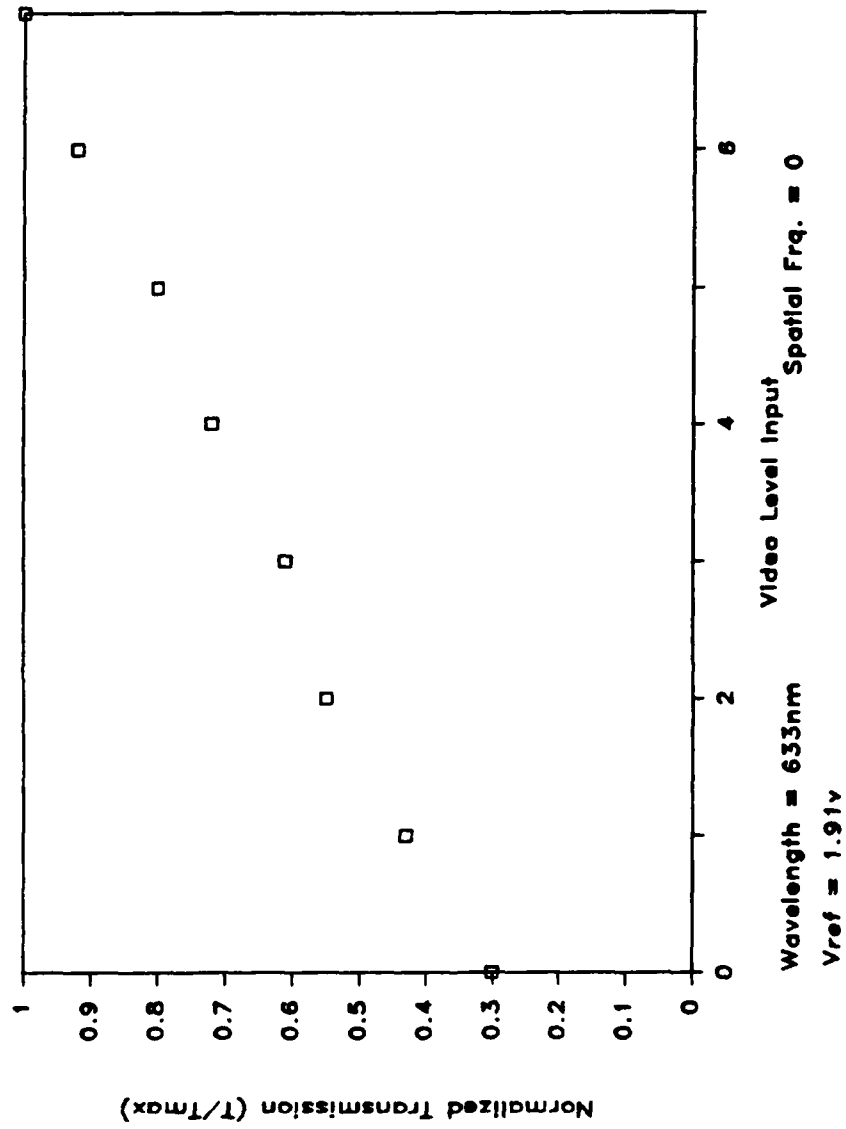
Graph 4.  Response Linearity.

the optical flatness of this device to be as shown in Figure 5. This
is a double-pass interferogram of the LCTV screen at a wavelength of
632.8 nm. This surface flatness is generally not sufficient for
coherent processing applications.

### Refresh Cycle Time

Due to the nature of liquid crystal display systems, the
individual pixels in the matrix are pulsed at regular intervals to
modulate them. This interval is referred to as the refresh cycle
time. Figure 4 shows the experimental set-up used to measure the
refresh cycle time. This geometry ensured that the area of
measurement covered only one pixel. The detector used in this
measurement was a photomultiplier tube and its output was input to
an oscilloscope. Figure 6 shows the refresh cycle time measured
in the middle of the liquid crystal display screen. The refresh
cycle time was found to be approximately 16.7 msec (approximately
60 Hz).

### Summary

In this chapter, the liquid crystal TV was characterized for
use as a spatial light modulator. The peak obtainable modulation
depth was found to be about 0.667, at $V_{ref}$ = 1.76 v. At this
brightness control setting, 2.5% of the incident light was
transmitted through the LCTV. Greater levels of transmission can
be achieved at the expense of reducing the modulation depth. It
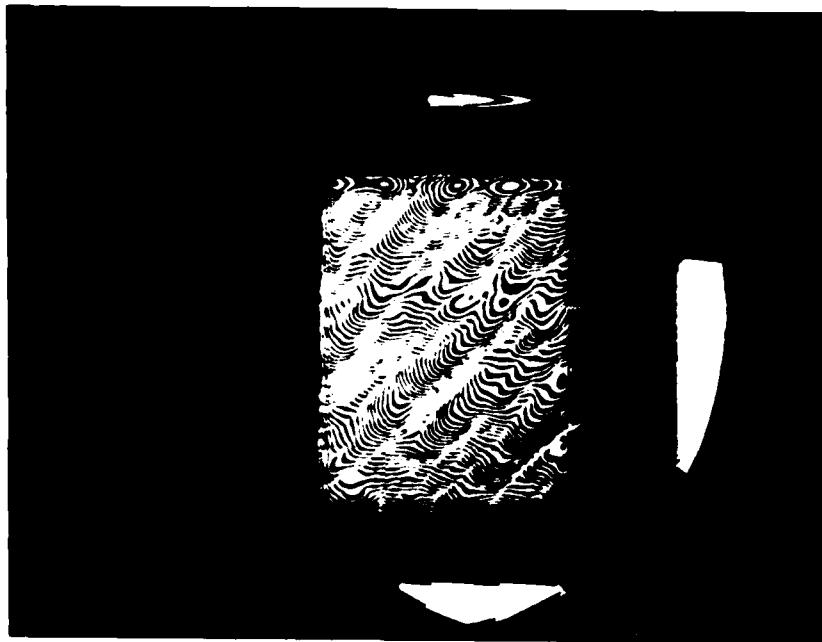
Figure 5.   Interferogram Showing Optical Flatness.
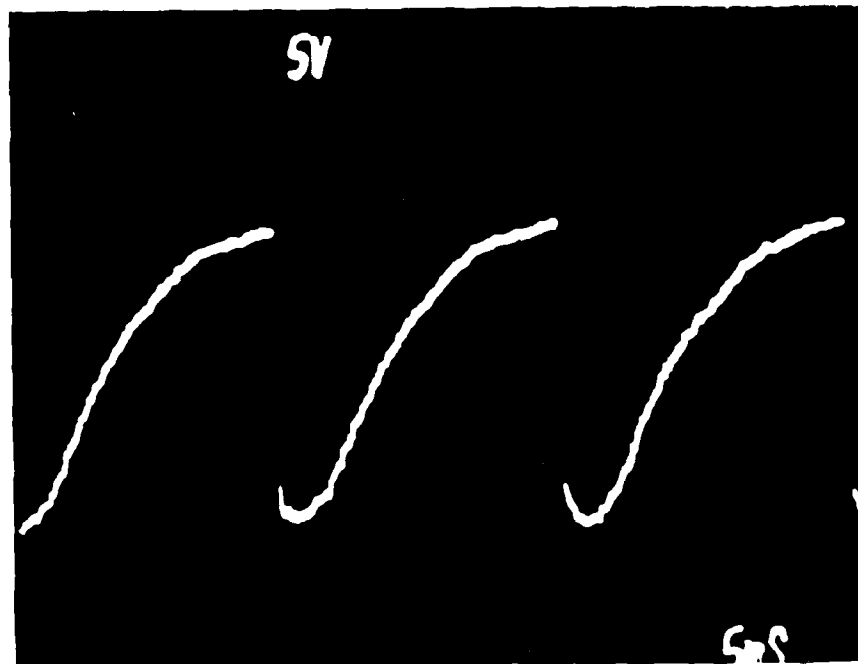
Figure 6.   Picture of Result Showing the Refresh Cycle Time.

was observed that a linear change in the gray level displayed on the LCTV resulted in an almost linear change in the transmitted light irradiance. The modulation transfer function was found to be fairly flat out to the Nyquist frequency. The optical flatness of the device was found to be very poor. The refresh cycle time was found to be about 0.0167 sec (approximately 60 Hz). These five parameters establish the basic operational characteristics of the spatial light modulator.

# CHAPTER III

## COHERENT OPTICAL PROCESSING WITH THE LCTV

### What is Coherent Optical Processing?

Coherent optical processing involves the modification of a
coherent input light distribution by some means. A typical
configuration to perform coherent optical processing is the 4f
processor, shown in Figure 7. In this set-up, $L_c$ collimates the
coherent input light from point source $P_1$. The input mask,
$t(x,y)$, is placed one focal length in front of $L_{ft}$, which is the
Fourier transforming lens. The Fourier transform of $t(x,y)$ is:

$$F\{t(x,y)\} = \int_{-\infty}^{\infty} \int t(x,y) \ell^{-j2\pi(f_x x + f_y y)} \, dxdy = T(fx,fy)$$

which appears at a distance one focal length behind $L_{ft}$, in the
Fourier transform plane. The spatial frequency filter is then
placed in this plane. $L_{in}$ performs a Fourier transform, and the
filtered, inverted image is displayed at a distance "f" behind
$L_{in}$.

The Fourier transform of an object is a linear, two-dimensional
integral transform. It allows us to analyze the spatial frequency
content of an object. Spatial frequencies may be thought of as
plane waves propagating in different directions (Goodman 1968).

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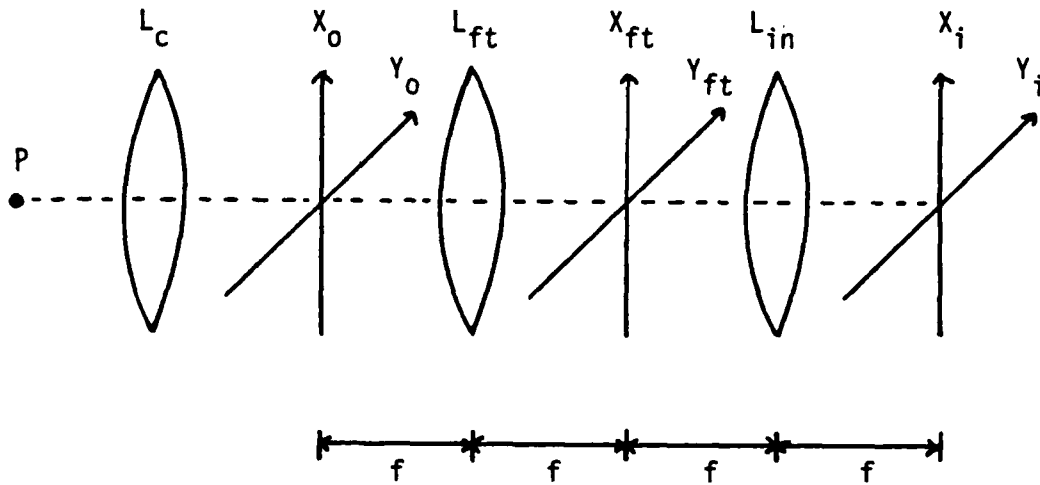
Figure 7.  Diagram of a 4f Processor.

Low spatial frequencies account for the slowly varying portions of the image.  High spatial frequencies contribute mainly to edges and other sharp transitions in the image (Gonzalez and Wintz 1977).

Spatial frequency filtering is the process of blocking or modifying certain spatial frequencies of an object in the Fourier transform plane.  For example, if the low spatial frequencies of an object were blocked (high pass filter), an edge enhancement of the object would be performed.  If low pass filtering (blocking high spatial frequencies) were employed, the image would appear softer, with less detail.  Recalling the 4f processor discussed above, the

lens, $L_{in}$, performs a Fourier transform on the filtered spatial frequency components. If the spatial frequency filter has a phase function associated with it, this must also be included in the Fourier transform integral (Vander Lugt 1974). Hence, the image has some distortion introduced into it because of this phase function. The spatial frequency filters discussed above had a transmission level of either one or zero. The LCTV used in our experiments does not (see Chapter II, Graph 1). If the liquid crystal TV is employed as a spatial frequency filter, the amplitude transmittance of the filter depends on the gray level (white through gray to black) displayed on the TV screen. The phase response of the LCTV is a function of the optical flatness of the display screen, as shown by the interferogram (Figure 5) shown in Chapter II.

## Spatial Filtering Demonstration

The experimental set-up used in the following coherent processing demonstration used a spherical mirror as the transforming element. A 35 mW helium-neon laser provided the coherent illumination, and a collimator was used to expand the beam. The experimental set-up is shown in Figure 8. The transparency used for this demonstration has the letter "A" superimposed over the letter "B". The "A" is made up of horizontal lines, while the "B" is made up of vertical lines, as shown in Figure 9. Due to the nature of the object transparency, we expect the "A" information was carried on the

2f

$L_C$    Transparency

Laser

Computer

50%
BS

Spherical
Mirror

A

$\overline{ABC}$ = f

B

SLM

C

Fourier
Transform
Plane

Fresnel Diffraction
Zone

D    Image Plane
$\overline{CD}$ = f
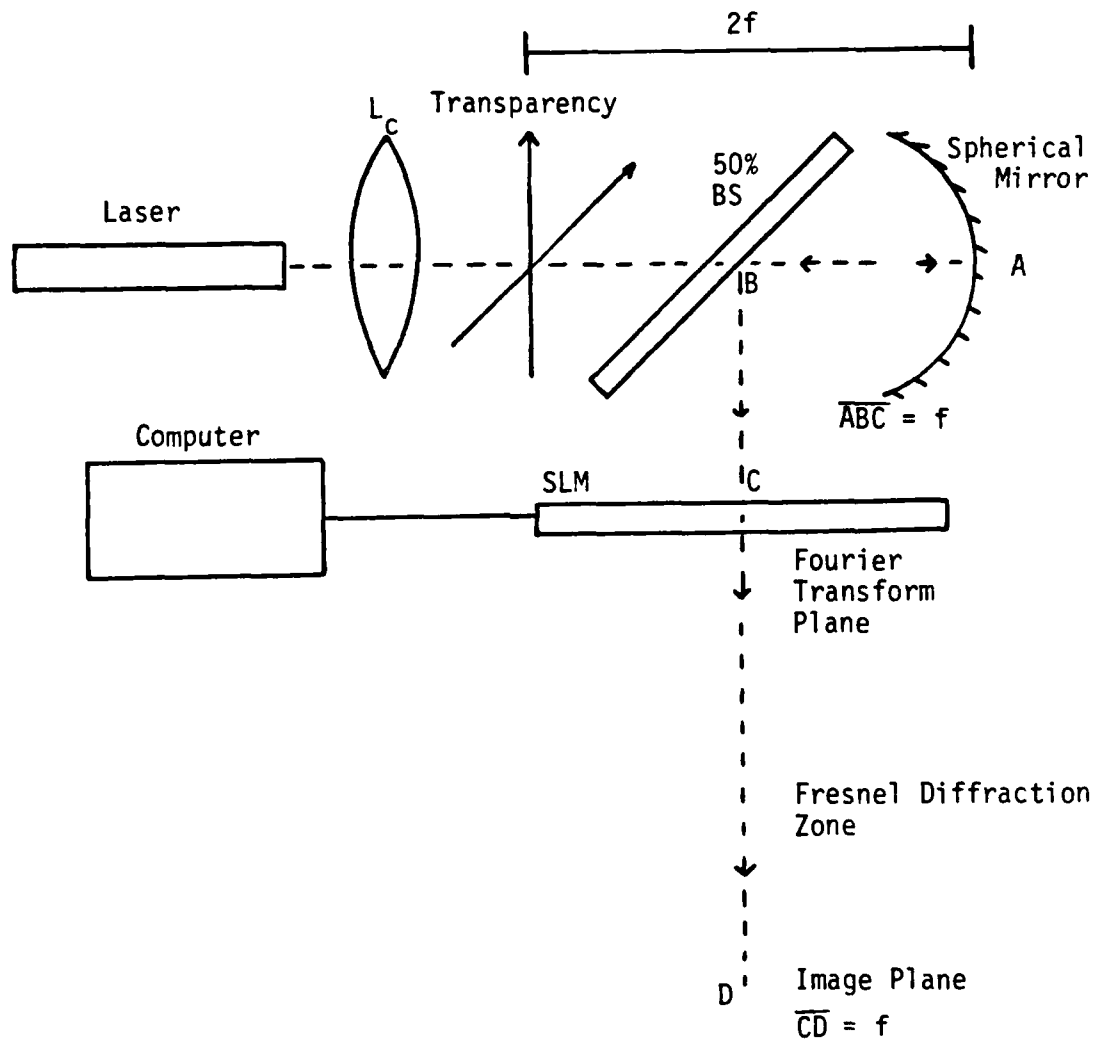
Figure 8.   Experimental Set-up to Demonstrate Coherent Optical
Processing.
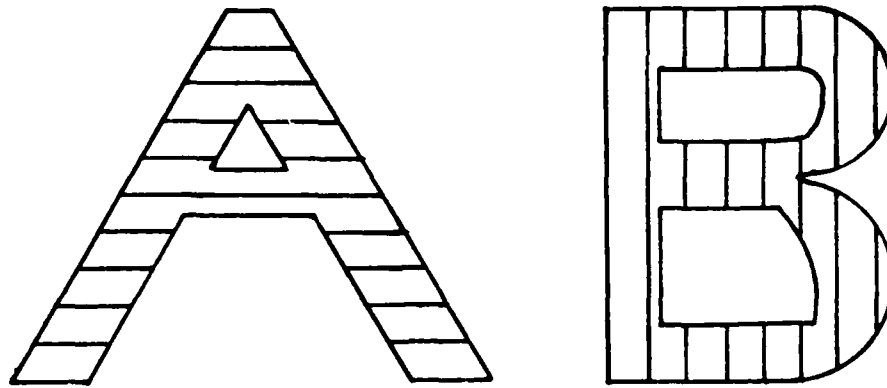
Figure 9.  Drawing of the A/B Transparency (the A and B are
Superimposed on the Transparency).

vertical orders and the "B" information was carried on the horizontal

orders in the Fourier transform plane.  Figure 10 shows the Fourier

transform of the A/B transparency.  The unfiltered Fresnel

diffraction pattern of the A/B transparency is shown in Figure 11.

Figure 12 shows a photo of the near field (Fresnel) diffraction

pattern after being filtered by a razor blade slit.  The filter

passed only the vertical components of the spatial frequency spectrum

of the A/B transparency.  Note the diffraction pattern is sharp and

clear, with the "B" component having been filtered out.  The LCTV

was used to generate a slit filter, similar to the filter described

above, using the program SLIT.BAS.  The SLM filtered Fresnel

diffraction pattern appears in Figure 13.  The "B" is more

attenuated than the "A", but is still present.  This is due to

the fact that the SLM does not have a one-zero transmission function.
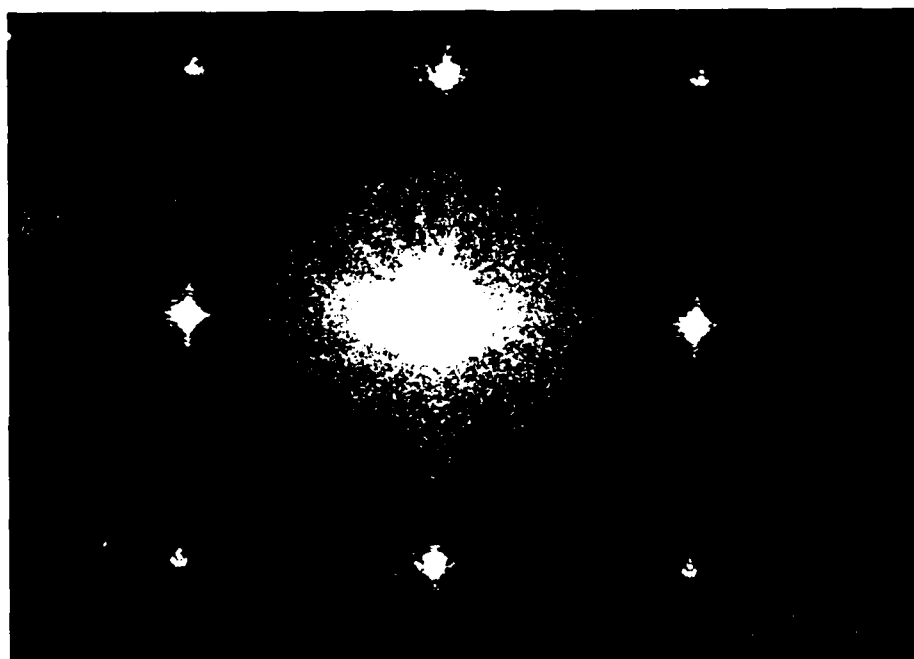
Figure 10.   Picture of Fourier Transform of A/B
             Transparency.
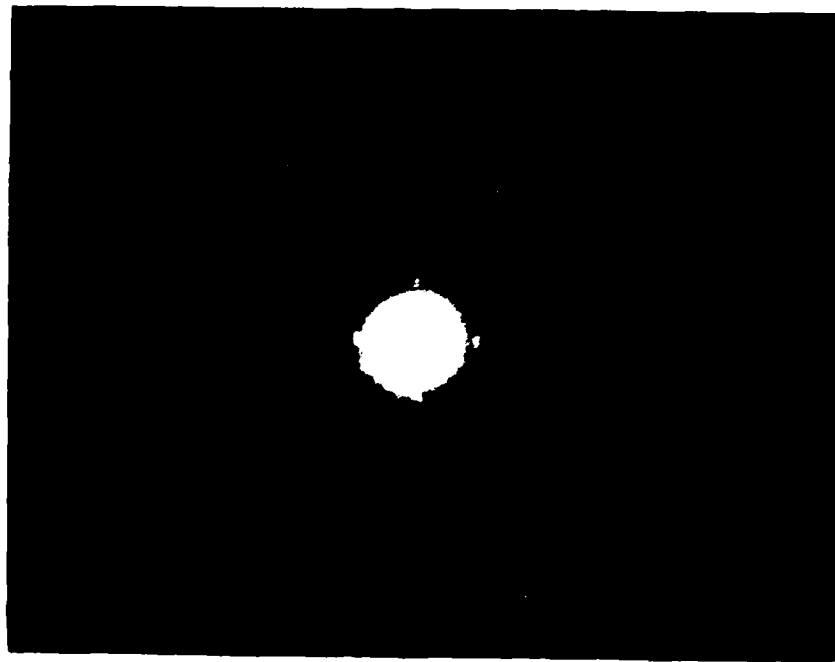
Figure 11.  Picture of Unfiltered Fresnel Diffraction
Pattern of A/B Transparency.

Figure 12.   Picture of Slit Filtered Fresnel Diffraction
             Pattern of A/B Transparency.
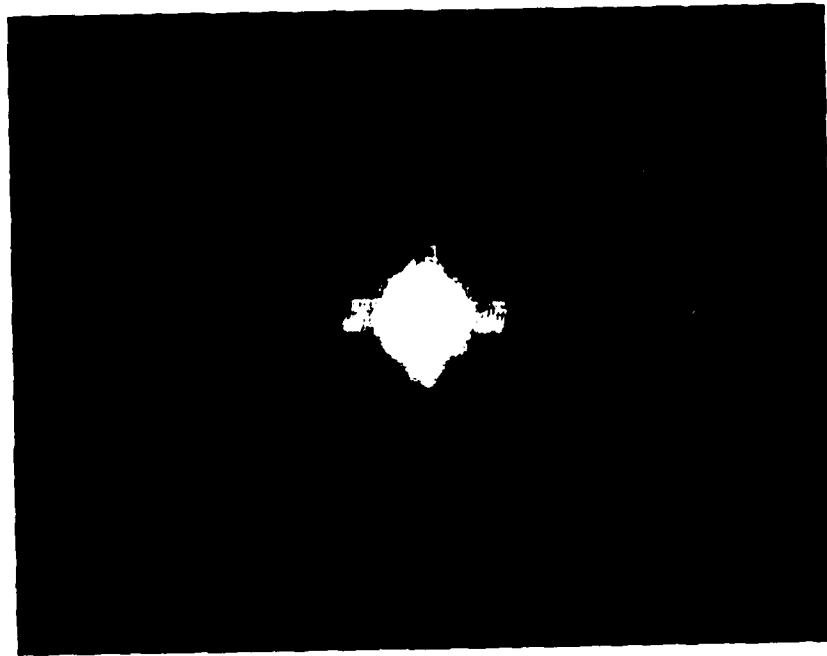
Figure 13.  Picture of SLM Filtered Fresnel Diffraction
Pattern of A/B Transparency.

Note the phase noise and scattered light which is seen due to
Fresnel diffraction of the non-uniform surfaces of the SLM. These
photos were not taken in the image plane because the overall
level of distortion in the image plane made the features harder
to recognize. The near field diffraction pattern shows the effect
in a more easily discernible manner.

## Summary

In this chapter, the liquid crystal TV was employed as a
programmable spatial filter to demonstrate coherent optical
processing techniques. The resulting photographs show that the
LCTV has limited usefulness as a coherent optical processor. Chapter
IV will explore the possibility of using the LCTV as an incoherent
optical processor.

# CHAPTER IV

## INCOHERENT OPTICAL PROCESSING WITH THE LCTV

### Why Incoherent Optical Processing

Incoherent optical processing involves the use of a partially coherent or incoherent light source. Coherent optical processing is used extensively today because of its ability to handle bipolar and complex functions. However, it has a number of shortcomings. First, coherent sources (lasers) are expensive. Also, the processing environment must be clean and free of contaminants and vibration. Finally, coherent processing systems are plagued by coherent artifact noise (Yu 1983). Incoherent processing has several inherent advantages. Incoherent processing systems suppress coherent artifact noise, as well as being fairly inexpensive. Also, the environmental requirements for incoherent processing systems are not nearly as rigorous as for a similar coherent system. In addition, most images of interest start out as incoherent images, in the first place, and their conversion to coherent images is costly and involved (Casasent et al. 1978).

Incoherent optical processing systems may be used for tracking, Fourier transforming, correlating, edge enhancement, speech processing, Schlieren methods and a host of other applications (Yu 1985). Many of these application areas have historically employed

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a number of moving parts, such as slits, masks, mirrors, reticles, etc. With the advent of low cost spatial light modulators, these moving parts can be eliminated, yielding mechanically simpler designs. These new implementations are more flexible due to the relative ease of manipulating bit-mapped video images on a computer, versus manipulation and modification of photographically produced masks or reticles.

## Image Multiplication Demonstration

A configuration which may find application to some of the above areas is an image multiplier. The image of interest, in this case a photographic slide, is multiplied by a square wave of variable spatial frequency by the LCTV. The square wave was generated by the program MTF.BAS (Appendix B). The experimental set-up is shown in Figure 14. There are other possible configurations of image multipliers, but the basic operation in shown in Figure 15.

## Summary

In this chapter, incoherent processing using the LCTV was discussed. A demonstration of white-light image multiplication was performed. The LCTV seems to perform better as an incoherent processor than as a coherent processor. This was expected due to the poor optical quality of the LCTV.

Computer

SLM

Incandescant
Bulb

Photographic
Slide

Diffuser
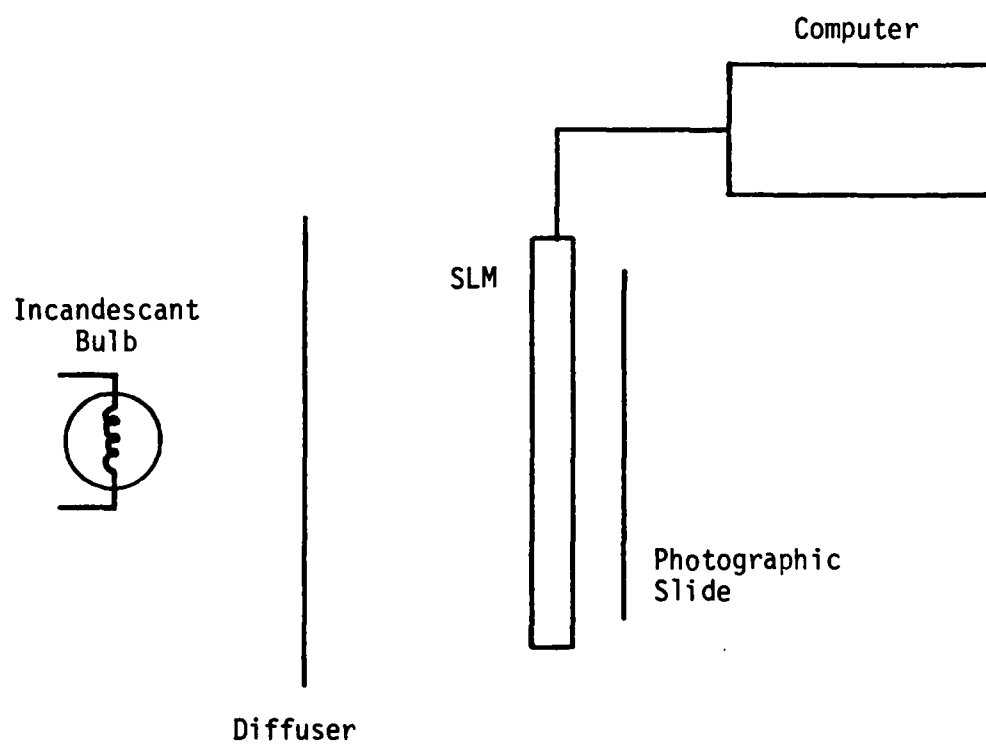
Figure 14.  Experimental Set-up to Demonstrate Incoherent
            Image Multiplication.
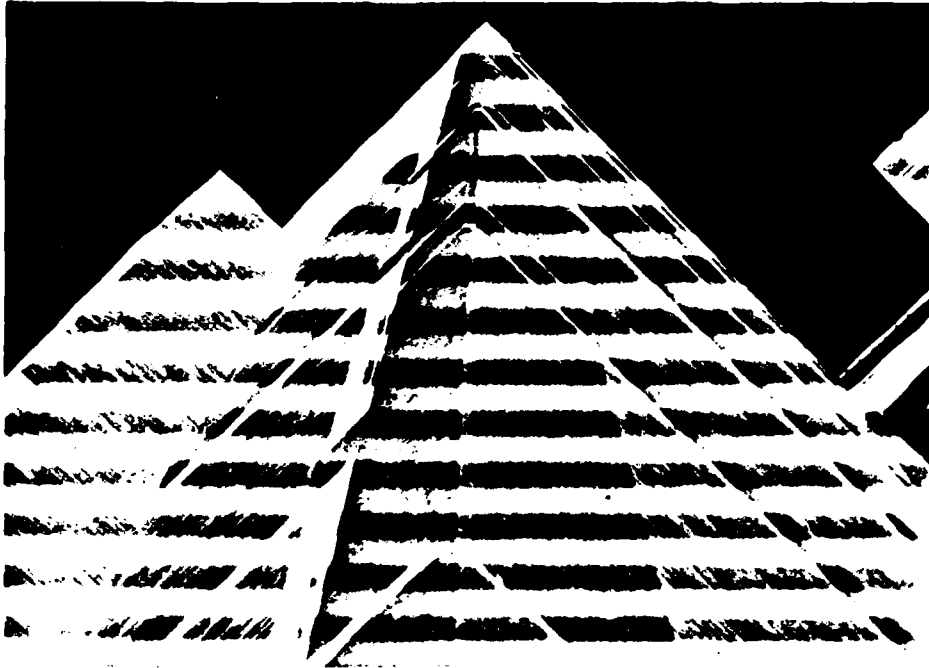
Figure 15.  Picture of Multiplied Image Using SLM.

# CHAPTER V

## CONCLUSIONS

### Suggestions for Further Work

In this section, the author would like to offer some ideas for additional research involving the liquid crystal TV. The maximum obtainable modulation depth of the SLM might be improved by improving the resolution of the "brightness" control. This could be done by adding a 10 turn, 100 ohm potentiometer in series with the brightness control. In addition, the primary problem with using the LCTV as a coherent processor was the poor optical flatness of the device. It may be possible to remove the existing polarizers and replace them with polarizers with better surface flatness. In this thesis, the LCTV was used as a binary filter. The LCTV will display at least eight video intensity levels. This is one aspect of the device that the author feels deserves additional attention, especially in the incoherent realm. Also, the device was utilized in the transmission mode. Further work might include characterization of the LCTV as a spatial light modulator utilizing the reflection mode.

### Summary

While the Radio Shack Model 16-151 Pocketvision television was designed to display information, it has been shown that the LC display may also function as a spatial light modulator. In this

research, the LCTV was used as a transmissive device.  The device
was characterized and simple examples of coherent and incoherent
optical processing were demonstrated.  This type of spatial light
modulator seems to be useful in low cost systems employing primarily
incoherent processing techniques.  An example of such an application
might be a pre-processor for  machine vision.  In this case, the
SLM would perform some initial processing functions, and would thereby
greatly reduce the computational complexity of the now pre-processed
data set.  This would alleviate some of the digital processing
burden required for certain image processing operations.

APPENDICES

## APPENDIX A

### HOST COMPUTER SPECIFICATIONS

The computer used for the work contained in this thesis was
an Atari 1200XL with one disk drive. The 1200XL has a 6502
microprocessor and 64K of RAM. While the 1200XL supports numerous
graphics modes, all work was done in graphics mode 8. In this
mode, there are 320 pixels (horizontal) by 192 pixels (vertical).
The 1200XL, when in a graphics mode, creates a dead area around
the display. Hence, the effective area of the LCTV was 120 pixels
by 96 pixels. In the vertical direction, for every 2 pixels the
computer turns "on", one comes "on" on the LCTV. This is not true
in the horizontal direction, where a mis-match exists. This
results in lines being cut-off. Therefore, care must be exercised
in choosing a computer that has a graphics display system compatible
with that of the LCTV.

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APPENDIX B

COMPUTER PROGRAMS

The following programs were written in Atari Basic:

MODULATION.BAS

MTF.BAS

LEVEL.BAS

SLIT.BAS

These programs were compiled using a Basic compiler and run as machine language programs. The Basic source code is provided for demonstration only.

```
10 REM *********************************
20 REM *                               *
30 REM *        MODULATION.BAS         *
40 REM *                               *
50 REM *             by                *
60 REM *                               *
70 REM *        Ed Raudenbush          *
80 REM *                               *
90 REM *           5 Aug 85            *
94 REM *                               *
98 REM *********************************
100 REM
110 REM This basic program allows the user to
120 REM switch the color of the graphics screen
130 REM to white or black.  This program was
135 REM used in the modulation depth measurement.
140 REM
150 REM
160 DIM C$(1)
170 GOSUB 300
180 GRAPHICS 8+16
185 SETCOLOR 2,0,X
190 IF PEEK(764)<>255 THEN GOTO 210
200 GOTO 190
210 POKE 764,255
220 IF X = 14 THEN GOTO 240
230 X = 14: GOTO 170
240 X = 0: GOTO 170
300 PRINT CHR$(125)
310 PRINT "Select 'WHITE' or 'BLACK' screen."
320 INPUT C$
330 IF C$ = "BLACK" THEN GOTO 350
340 X = 14: GOTO 360
350 X = 0
360 RETURN
```

```
10 REM ********************************
20 REM *                              *
30 REM *           MTF.BAS            *
40 REM *                              *
50 REM *             by               *
60 REM *                              *
70 REM *       Ed Raudenbush          *
80 REM *                              *
90 REM *         15 Nov 85            *
94 REM *                              *
98 REM ********************************
100 REM
110 REM This BASIC program generates alternating black
110 REM and white bars used in the measurement of
120 REM the modulation transfer function (MTF).
130 REM
140 REM
160 DIM C$(1)
170 GOSUB 800
200 LET A = INT(2*(14.77/SF))
210 GRAPHICS 8+16
220 SETCOLOR 2,0,Z
230 SETCOLOR 1,0,Y
240 COLOR 1
250 PLOT 0,110
260 DRAWTO 319,110
270 PLOT 0,111
280 DRAWTO 319,111
290 LET Z = A/2-1
300 IF Z = 0 THEN GOTO 360
310 FOR I = 1 TO Z
320 PLOT 0,110-I
330 DRAWTO 319,110-I
335 PLOT 0,111+I
340 DRAWTO 319,111+I
350 NEXT I
360 LET C = 110-Z-1
370 FOR H = C-A TO C-2*A+1 STEP -1
380 IF H <= 0 THEN GOTO 440
390 PLOT 0,H
400 DRAWTO 319,H
410 NEXT H
420 C = C-2 A
430 GOTO 370
440 LET C = 111+A/2
450 FOR H = C+A TO C+2*A-1
460 IF H >= 191 THEN GOTO 540
480 PLOT 0,H
490 DRAWTO 319,H
500 IF H = 319 THEN GOTO 300
510 NEXT H
520 LET C = C+2*A
530 GOTO 450
```

```
540 IF PEEK (764)<>255 THEN GOTO 560
550 GOTO 540
560 POKE (764,255)
570 IF Y = 14 THEN GOTO 590
580 Y = 14: Z = 0: GOTO 200
590 Y = 0: Z = 14: GOTO 200
800 GRAPHICS 0
810 PRINT "AVAILABLE SPATIAL FREQUENCIES"
820 PRINT: PRINT
830 PRINT "    1.48 LP/mm"
840 PRINT "    0.74 LP/mm"
850 PRINT "    0.49 LP/mm"
860 PRINT "    0.37 LP/mm"
870 PRINT "    0.30 LP/mm"
880 PRINT "    0.25 LP/mm"
890 PRINT "    0.21 LP/mm"
900 PRINT "    0.18 LP/mm"
910 PRINT "    0.16 LP/mm"
920 PRINT "    0.15 LP/mm"
930 PRINT "    0.10 LP/mm"
940 PRINT "    0.07 LP/mm"
950 PRINT "    0.06 LP/mm"
960 PRINT "    0.05 LP/mm"
970 PRINT "Select the exact spatial frequency ."
972 INPUT SF
975 PRINT: PRINT
980 PRINT "Select center bar (WHITE) or (BLACK)."
985 INPUT C$
990 IF C$ = "BLACK" THEN GOTO 1010
1000 Y = 0: Z = 14: GOTO 1020
1010 Y = 14: Z = 0
1020 GRAPHICS 0
1030 PRINT: PRINT
1040 PRINT "Spatial frequency = " ;SF; " LP/cm"
1050 PRINT: PRINT
1060 PRINT "Center bar will be ";C$
1070 PRINT: PRINT
1080 PRINT "After the bars are displayed,"
1090 PRINT "*** the COLOR of the center bar may be"
1100 PRINT " changed by hitting any key ***"
1105 FOR X = 1 TO 200: NEXT X
1107 SF = SF*10
1110 RETURN
```

```
10 REM *********************************
20 REM *                               *
30 REM *          LEVEL.BAS            *
40 REM *                               *
50 REM *             by                *
60 REM *                               *
70 REM *        Ed Raudenbush          *
80 REM *                               *
90 REM *          12 Sep 85            *
94 REM *                               *
98 REM *********************************
100 REM
110 REM This basic program allows the user to
120 REM select the color of the graphics screen
130 REM in 8 levels from white (0) to black (7).
135 REM This program was used in
137 REM the sensitivity measurement.
140 REM
150 REM
155 GOSUB 300
160 GRAPHICS 8+16
165 SETCOLOR 2,0,X
170 IF PEEK(764)<>255 THEN GOTO 190
180 GOTO 170
190 POKE 764,255
200 IF X = 14 THEN GOTO 220
210 X = X+2: GOTO 155
220 X = 0: GOTO 155
300 PRINT CHR$(125)
310 PRINT "Select gray level (0 - 7)."
320 INPUT C
330 X = 2*C
340 RETURN
```

```
10 REM *********************************
20 REM *                               *
30 REM *          SLIT.BAS             *
40 REM *                               *
50 REM *            by                 *
60 REM *                               *
70 REM *       Ed Raudenbush           *
80 REM *                               *
90 REM *          5 Jan 86             *
94 REM *                               *
98 REM *********************************
100 REM
110 REM This BASIC program generates a white slit
120 REM on a black background used in the
125 REM optical processing demonstrations.
130 REM
140 REM
145 GOSUB 400
150 GRAPHICS 8+16
160 SETCOLOR 2,0,Z
170 SETCOLOR 1,0,Y
180 COLOR 1
190 FOR A = X1 TO X1+W
200 PLOT X1,Y1
260 DRAWTO X1,Y1+L
270 IF PEEK (764)<>255 THEN GOTO 290
280 GOTO 270
290 POKE 764,255
300 GOTO 145
400 PRINT CHR$(125)
410 PRINT "There are 160 possible horizontal"
420 PRINT "positions and 96 possible vertical
positions."
430 PRINT
440 PRINT "Select top left location of slit (x,y)"
450 INPUT X1,Y1
460 PRINT "Select length of slit"
470 INPUT L
480 PRINT "Select width of slit"
490 INPUT W
500 RETURN
```

## APPENDIX C
## PHOTOGRAPHIC INFORMATION

Most photographs appearing in this thesis were taken with a Cannon AE-1 35 mm, SLR camera, operated in the manual mode. The film used was Kodak Tri X black and white film (ISO 400). The oscilloscope photographs were taken using a Tektronix C-30 camera and Polaroid Series 100 film. The magnification setting was 0.9, shutter speed 1/30 s, and 5.6 f/stop.

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# END

# DTIC

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